# The 3D Structure of Spilling Breakers

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## LONG-TERM GOALS

The long-term goal of this project is to elucidate the dynamics of spilling breakers including the three-dimensional structure of the surface and the subsurface flow field and to aid in the development of remote sensor response models by performing experiments with simultaneous wave and remote sensor measurements.

## OBJECTIVES

Nearly all calculations and measurements of breaking waves assume the wave profiles and flow fields are two-dimensional. Though this assumption may be correct before the waves become turbulent, once transition to turbulent flow begins, the real flow becomes highly three dimensional. The three-dimensional structure and motion of the free surface is important for the dynamics of the breaking process, the mixing of the surface water and the response of remote sensors. In the present research program, we are measuring the three-dimensional surface and subsurface flow structure of spilling breakers and are collaborating with investigators from other institutions who are performing infrared and radar measurements during our experiments and providing calculations of radar response using our wave profile data as input.

## APPROACH

The experiments are being performed in a tank that is 15 m long, 1.2 m wide and 1.0 m deep. The breakers are generated with a programmable plunger-type wave maker. (A wind tunnel will be added to the wave tank this spring.) Both dispersively focused wave packets and modulated wave trains are used to create breaking waves. A low vibration, programmable instrument carriage rides above the tank on precision rails. The carriage and the wave maker are controlled by a single computer, thus making it possible to coordinate the motions of the two devices. With this system, measuring instruments that are placed on the carriage can be made to follow a breaking wave crest as it moves along the tank.

Several measurement techniques are now being used or developed in our laboratory to study these breakers. The first is the measurement of two-dimensional crest profile histories. In these measurements, a laser light sheet is projected vertically onto the wave crest from the instrument carriage. The water is mixed with fluorescent dye. A high-speed camera mounted on the instrument carriage and oriented perpendicular to the light sheet photographs the intersection of the light sheet and

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14. ABSTRACT
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the water surface, thus yielding, after image processing, the temporal evolution of the surface profile. This system has been used to measure the crest profile history as seen both from the side with the light sheet oriented along the streamwise direction (streamwise profiles) and as seen from in front of the wave crest with the light sheet oriented along the crest (cross-stream profiles).

In order to obtain the temporal evolution of the three-dimensional surface shape in the turbulent patch generated during breaking, a color slope device is being constructed. In this device, a colored optical light source is used to produce upward traveling light whose color changes continuously with angle from the vertical. A color camera system views the illuminated patch of the surface from directly overhead. The images are processed to convert the color at each pixel in the image to a water surface slope. The slope map is then integrated to obtain the surface height field. It is planned to obtain such images at a rate of 200 Hz. The slope image sequences will be used to determine the appearance and behavior of streamwise surface structures which are the result of subsurface streamwise turbulent flow structures. It has been found in turbulent boundary layers that these structures are responsible for much of the transport of streamwise momentum in the direction normal to the wall. It is expected that the same may be true in turbulence generated at the free surface by breaking waves.

In the future, subsurface flow field measurements will be made using particle image velocimetry. However, these measurements are still in the planning stage.

In addition to above measurements, we have made radar and infrared measurements of our waves in conjunction with Mark Sletten and Geoffrey Smith of the Naval Research Laboratory, respectively. The radar measurements have been made simultaneously with our crest profile measurements and with the radar antennae mounted on our moving instrument carriage. The infrared measurements will give us information on the breaker-induced disruption of the free-surface thermal layer. Plans are underway to use the color wave slope device described above simultaneously with the infrared measurements in order to have both geometric and thermal measurements of the free surface behavior.

## WORK COMPLETED

Several experiments have been performed including measurements of the streamwise and cross-stream structure of the crests of spilling breakers, preliminary measurements of the temperature of the breaking crests surface with an IR sensor, and preliminary simultaneous measurements of the streamwise wave profile history and radar response of several spilling breakers. In addition, we have nearly completed the construction of an optical device that can measure the distribution of surface slope over an area of about 10 cm by 10 cm with a spatial resolution of 256 by 256 pixels and a frame rate of 250 Hz.

## RESULTS

An example of a crest profile history with the light sheet oriented in the streamwise direction is given in Figure 1a. This breaker was generated by the dispersive focusing method using an average wave packet frequency of $f_0 = 1.15$ Hz. Since the measurements are taken moving with the crest, it appears stationary in the profile history. Note from the figure that as the crest steepens, a bulge forms on the front face (on the left). After a short time, the leading edge of the bulge (toe) begins to move down slope and the surface profile between the toe and the crest becomes rough indicating that the underlying flow has become turbulent. Large ripples develop in this region; these ripples move over

the crest and are left behind the wave. An example of a crest profile history with the light sheet oriented along the wave crest is shown in Figure 1b. Each profile plotted is the difference between the measured profile and its average value. The profile history shows that the crest shape contains cross-stream ripples that appear almost as standing waves. In order to analyze this data further, the average of each profile and the standard deviation about the average of each profile was computed. This calculation was repeated for 5 experimental runs for a breaker generated with $f_0$ = 1.42 Hz and for 2 experimental runs for a breaker generated with $f_0$ = 1.15 Hz. The wavemaker motions at the two frequencies were Froude scaled so that in the absence of surface tension and viscosity, one would expect the wave breaking events to be scaled versions of one another. The average and standard deviation for each run were averaged over the runs at each frequency and the results for both waves are plotted in Figure 2. In the figure, the height and standard deviation have been non-dimensionalized by the wavelength, $\lambda_0$, computed from linear theory using the wave packet average frequency ($\lambda_0 = g/(2\pi f_0^2)$ where g is gravity) and time has been non-dimensionalized with $T_0 = 1/f_0$. Each of the two average height versus time curves show a rippled shape that starts near the time of maximum height for the wave. Since the ripples are strong features in these curves, which have been averaged over several waves, the data indicates that the ripples are repeatable structures in the surface motion. It is thought that the ripples are manifestations of subsurface vortices generated during the spilling process. Note that the two average height versus time curves follow a similar average path for the two waves but that the ripples appear at a later time in the wave evolution and have a shorter dimensionless period for the $f_0$ = 1.42-Hz wave.

Another interesting aspect of these waves is the propagation of cross-stream ripples as seen in Figure 1a. In order to quantify the characteristics of these ripples, a program was written to locate the local minima (ripple troughs) in each profile. These minima were then tracked from profile to profile. The wavelength of a ripple was taken as the distance between neighboring minima and the phase speed of the ripple was taken as the average of the slopes of the trajectories of the two minima adjacent to a particular ripple. The results for three separate breaking events are shown in Figure 3. Figure 3a is a plot of the wavelength of the first, second and third ripples of each breaker plotted versus time while Figure 3b is a plot of the phase speeds of the first, second and third ripples plotted versus time. It is interesting to note that both the wavelengths and the phase speeds increase nearly linearly in time and that the range of speeds and wavelengths is the same for the three ripples. Also, the trajectories are remarkably similar from breaker to breaker.

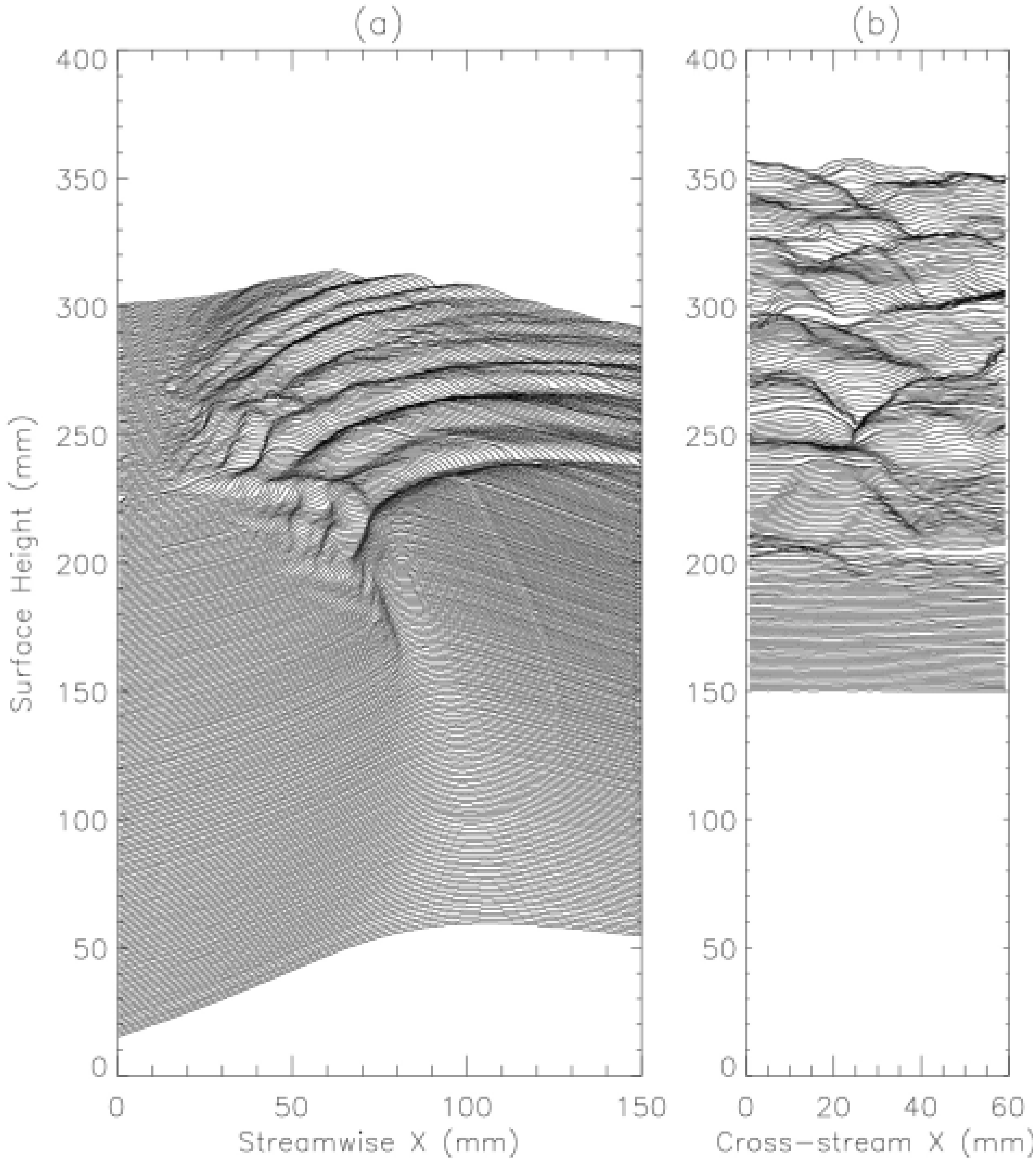


***Figure 1. Crest profile histories, $f_0$ = 1.15 Hz. (a) Surface height versus streamwise distance at various times during the breaking process. In these wave-fixed coordinates, the flow is moving from left to right. (b) Surface height versus cross-stream distance (i.e. distance along the crest) at various times during the breaking process. In both plots, each profile is raised by 1 mm above the previous profile. Thus, time increases in the upward direction. The time between profiles is 3.33 ms.***

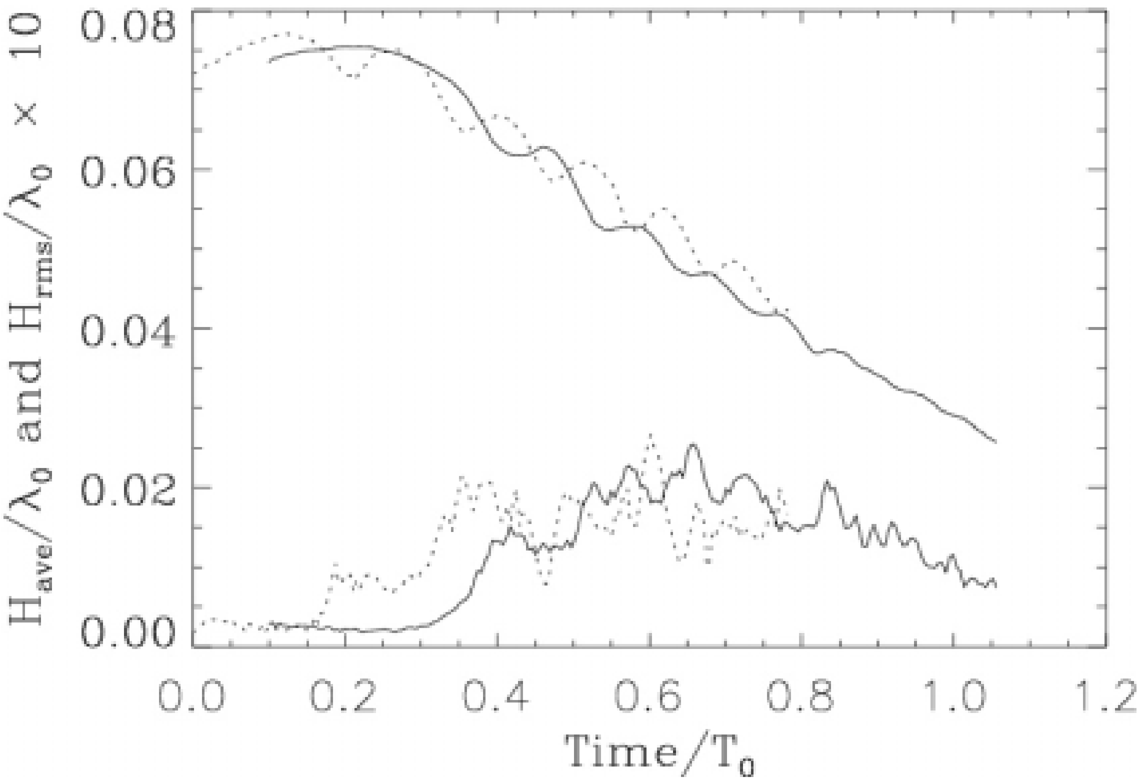


***Figure 2. Average (top curves) and standard deviation (bottom curves) of the crest height versus time for two spilling breakers generated with wave packets with average frequencies of $f_0$ = 1.42 and 1.15 Hz. The crest height and standard deviation are normalized by the nominal breaker wavelength, ($\lambda_0 = g/(2\pi f_0^2)$). $T_0 = 1/f_0$.***

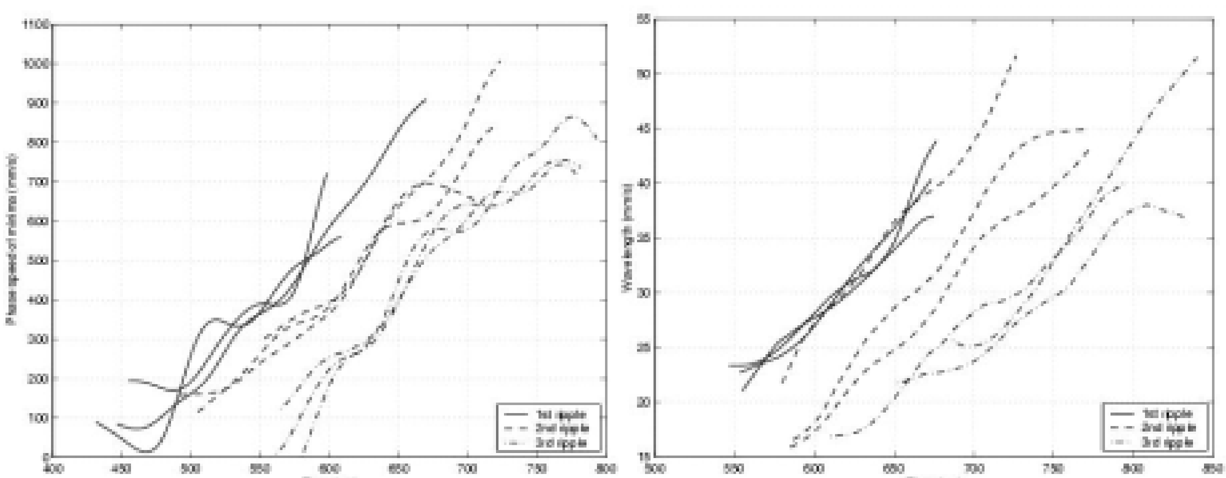

***Figure 3. Phase speed (left plot, relative to the crest) and wavelength (right plot) versus time for the first, second and third cross stream ripples generated during three spilling breaking events like that shown in Figure 1. Both the phase speed and the wavelength increase roughly linearly with time and with the same rates, respectively, for all three ripples.***

## IMPACT/APPLICATIONS

The experiments are intended to provide better understanding and data for the development of models of the response of remote sensors to breaking waves.

## TRANSITIONS

This work is being transitioned to the Navy in two ways. First, both the infrared and radar measurements have been performed in our laboratory by personnel from the Naval Research Laboratory and we are working jointly with personnel at NRL to interpret the sensor data in light of the wave profile data. Second, we are giving our wave profile data to Prof. J. West at Oklahoma State University who is using the data as input in calculations of radar response. A paper describing the results of these calculations was published this year. Prof. J. West is also working with Dr. Mark Sletten of NRL who is performing the radar measurements in our laboratory.

## RELATED PROJECTS

We have two related grants. The first is with the National Science Foundation. In this work, we are studying the effect of surfactants on spilling breakers. This is a joint project with Prof. G. Korenowski of the Rensselaer Polytechnic Institute. The second grant is with the Office of Naval Research. This grant involves a laboratory investigation of the breaking bow waves of naval combatant ships.

## PUBLICATIONS

Ja, S.-J., J. C. West, H.~Qiao and J. H. Duncan, "Mechanisms of Low-Grazing-Angle Scattering from Spilling Breaking Water Waves," *Radio Science*, Vol. 36, No. 5, pp. 981-998, Sept./Oct. 2001.

Steinbach, T., X. Liu, and J. H. Duncan, "The Cross-Stream Crest Profile of Gentle Spilling Breakers," Proceedings of the Euromech Conference on the Interaction of Strong Turbulence and the Free Surface, Genoa, Italy, September 2000, in press.